Extra Physics with an ABS and a Lamb-shift Polarimeter

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The polarized internal gas target of the ANKE experiment is only used for a few months per year for hadron physics at the cooler synchrotron COSY. In the meantime, the whole setup or components like the ABS or the Lamb-shift polarimeter can be used for other experiments. We present various projects, from nuclear fusion, atomic and molecular physics to a neutrino experiment, for which the existing hardware can be used.

Keywords: polarized source, Lamb-shift polarimeter, polarized fusion, hyperfine spectroscopy, polarized molecules, bound beta decay

1. Polarized Fusion

Since more than 40 years it is known that polarizing the fuel particles will change the total cross section of the nuclear fusion reactions. For the $d+^3He$

and the $d + t$ reaction it is expected and has been shown, that aligned spins will increase the fusion rate by a factor up to 1.5[1] because both reactions have a $J^{\pi} = 3/2^{+}$ resonance at low energies. For the $d + d$ reactions no valid theoretical guidance exists. They require consideration of s, p, and d waves in 16 transition matrix elements, which would allow a neutron-lean fusion reactor via the $^{3}He + d$ reaction if the $d + d$ neutrons could be suppressed. This had been postulated in the $d + d$ spin-quintet state for which quite different predictions[2–9] exist (Fig. 1). To determine the degree of quintet-state suppression a direct spin-correlation cross section experiment at low energies is in preparation.

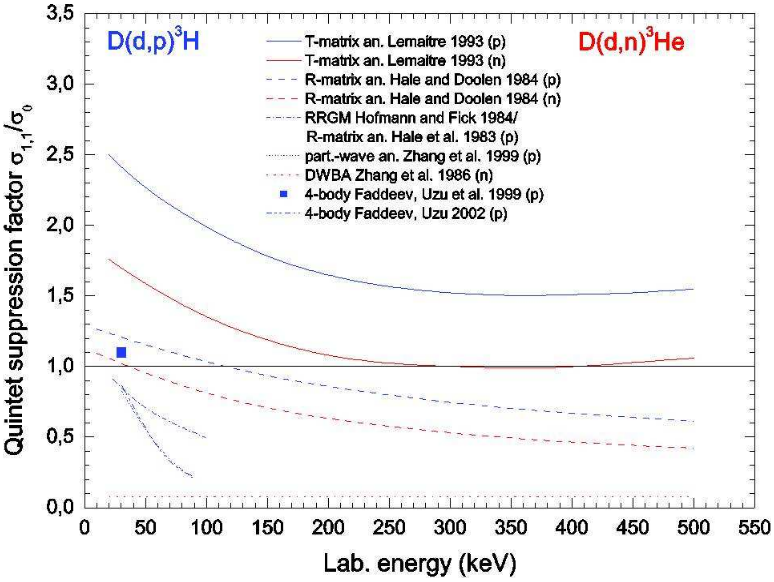

Fig. 1. Different predictions for the ratio of the double polarized total cross section $\sigma_{1,1}$ and the unpolarized cross section σ_0 for both dd-fusion reactions.

In an earlier setup it was planned to use a polarized atomic beam source (ABS), a donation from the University of Cologne,[10] to produce the polarized deuterium jet target and, by ionizing these atoms and deflecting them back, the polarized deuteron beam at the same time. Just a few days before this conference the KVI, Groningen, The Netherlands, generoulsy agreed to provide their polarized ion source POLIS[11] for the present project. This source consists of an ABS, an ECR ionizer and a Lamb-shift polarimeter.

At deuteron beam energies up to 32 keV intensities up to 20 μA can be provided. Together with the expected jet-target density of 2×10^{11} atoms/cm^2 a luminosity of 4×10^{25} cm^{-2}s^{-1} will be possible. This means, that at 30 keV, which will be a reasonable energy for coming fusion reactors, a count rate of 50 counts/s is possible. Therefore, the quintet suppression factor can be measured within 2 months of beam time with a statistical error of 1%. For an ion-beam energy of 20 keV it will take 8 months due to the lower total cross section. In addition, several spin-correlation coefficients can be measured, which will help to understand the reaction mechanism.

2. Hydrogen Spectroscopy

With the spinfilter,[12] the central component of the Lamb-shift polarimeter,[13] it is possible to produce a beam of metastable hydrogen (deuterium) atoms in just one Zeeman state. With induced single transitions between the different Zeeman states of the $2S_{1/2}$ and the $2P_{1/2}$ hyperfine states, the Breit-Rabi diagrams, including the hyperfine energy splittings, the Lamb shift and the Lande factors can be measured very precisely.

2.1. *The Breit-Rabi Diagram of the 2S State of Hydrogen and Deuterium*

With a setup similar to that of the *Atomic Beam Resonance Method*[14] (Fig. 2), the complete Breit-Rabi diagram of the 2S state of hydrogen and deuterium can be measured. In our setup, the *analyzing magnets* of the Rabi apparatus are replaced by spinfilters.

In an electron-impact ionizer H_2 (D_2) molecules are dissociated and ionized. With acceleration of the ions to energies between 300 and 2000 eV, beam intensities up to 10 μA can be achieved. After deflection to a horizontal beam direction, a Wien filter is used to separate the protons from the other ions, which originate from the residual gas. By charge exchange with cesium vapour,[15] metastable hydrogen atoms in the state $2S_{1/2}$ are produced from about 15% of the protons. In the first spinfilter all metastable atoms except those in one Zeeman state are quenched into the ground state. Only metastable atoms in the Zeeman states $\alpha1$, $\alpha2$ or, using a subsequent Sona transition, $\beta3$ remain in the beam. In a homogeneous magnetic field, magnetic dipole transitions are induced with the magnetic field vector parallel to the velocity direction of the hydrogen atoms in order to avoid longitudinal Doppler shift and broadening. The direction of a static magnetic field, produced by two Helmholtz coils, can be aligned either parallel or perpendicular to the velocity direction of the atoms. Thus, for a transverse magnetic field, the transitions $\alpha 1 \rightarrow \alpha 2$, $\alpha 1 \rightarrow \beta 4$, $\alpha 2 \rightarrow \alpha 1$ and $\alpha 2 \rightarrow \beta 3$ can be measured. The second spinfilter is used to verify the induced transitions. As an example in Fig. 2 atoms in the metastable state $\alpha 1$ are leaving the first spinfilter and transfered into $\alpha 2$ in the transition unit. The second spinfilter is set to transmit the state $\alpha 2$ only. Therefore, metastable atoms can produce light in the quenching chamber only if the transition from state $\alpha 1$ into state $\alpha 2$ has occured in the transition unit. The large number of 10^5 photons/s detected in the photomultiplier allows to reach a statistical error comparable to that of the best measurements[16] in 20 min. In addition, the hyperfine-splitting energy can be measured independently of the magnetic field as a combination of the transition frequencies ($\alpha 1 \rightarrow \beta 4$) - ($\alpha 2 \rightarrow \beta 3$) or ($\alpha 1 \rightarrow \alpha 2$) + ($\beta 3 \rightarrow \beta 4$). Therefore, a huge number of individual and direct measurements is possible. To increase the precision of the experiment the halfwidth of the measured resonances can be decreased with use of the so called *separated oscillatory field method*[17] and with much slower metastable hydrogen beams produced, e.g., with the ABS and excited by electron bombardment. By that, it will be possible to reach the precision of current laser-spectroscopy experiments and to measure the g-factor of the 2S state with a precision of 10^{-8}.

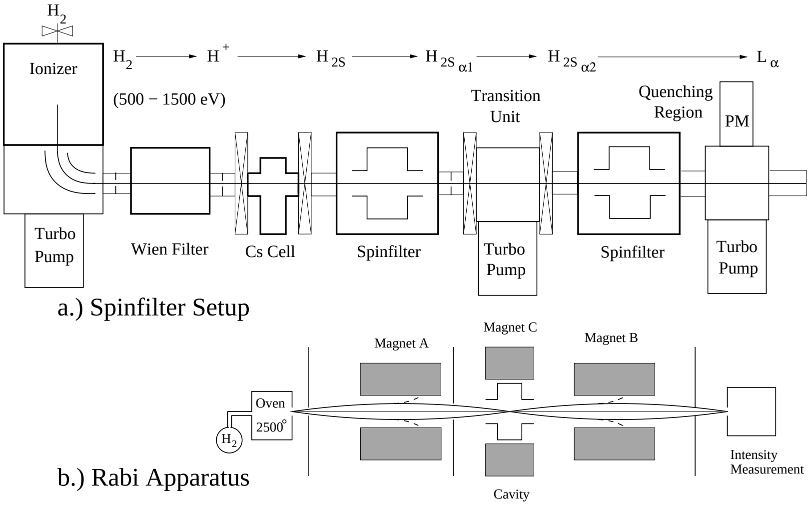

Fig. 2. a.) The setup for the measurement of the complete Breit-Rabi diagram of the 2S states of hydrogen or deuterium. b.) The schematic of the classical Rabi apparatus.

2.2. *The Breit-Rabi Diagram of the 2P state of Hydrogen and Deuterium*

With induced electric-dipole transitions from the single 2S-Zeeman states into single 2P states behind the spinfilter, the classical Lamb shift[18] and the complete Breit-Rabi diagram of the 2P state can be measured. In contrast to the original Lamb measurements today it is possible to change the RF frequency without changing of the RF power in a constant magnetic field by a Lecher TEM waveguide.

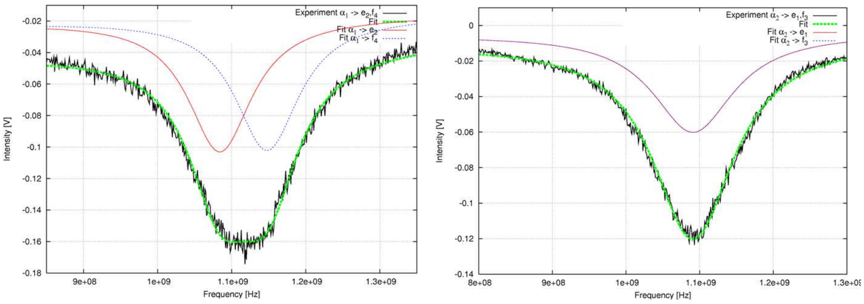

Fig. 3. The observed transitions ($\alpha 1 \rightarrow f4$) and ($\alpha 1 \rightarrow e2$) (left) or ($\alpha 2 \rightarrow f3$) and ($\alpha 2 \rightarrow e1$) (right) at a small vertical magnetic field in the transition region.

In a proof-of-principle measurement metastable hydrogen atoms in the HFS $\alpha 1$ or $\alpha 2$ are selected in the spinfilter and reach the TEM waveguide. For a small transverse magnetic field close to 0 G the transitions ($\alpha 1 \rightarrow f4$) and ($\alpha 1 \rightarrow e2$) (Fig. 3, left) or ($\alpha 2 \rightarrow f3$) and ($\alpha 2 \rightarrow e1$) (Fig. 3, right) are observed. The difference between the two resonances of the transitions ($\alpha 1 \rightarrow f4$) and ($\alpha 1 \rightarrow e2$) corresponds to the hyperfine splitting energy of the $2P_{1/2}$ state. The result from a fit of 60 (2) MHz agrees with the earlier result of 59.22 (14) MHz.[17] The transition frequencies from the $2S_{1/2}$ into the $2P_{1/2}$ state together with the HFS of these states allows to obtain the classical Lamb shift. As a first result a value of 1057(1) MHz could be determined. The dominant error, which is up to 3 orders of magnitude larger compared to the best values, is produced by the inhomogeneity and the uncertainty of the magnetic field. An error of $\Delta B = 0.5$ G, e.g., corresponds to an error of $\Delta f = 1$ MHz.

3. Polarized Molecules

When polarized hydrogen atoms recombine in a storage cell, the residual H_2 molecules may still be nuclear polarized.[19] In a collaboration between PNPI, University of Cologne and FZ Jülich a device was built (Fig. 4) to measure the polarization of hydrogen atoms and hydrogen molecules after recombination of polarized atoms depending on different materials, temperatures and magnetic fields. In a superconducting solenoid polarized atoms from the ABS partly recombine in a T-shape storage cell, where the inner surface can be covered with different materials. Both, atoms and molecules, are ionized afterwards by electron bombardment and the protons and H_2^+ ions produced are accelerated to an energy of a few keV. Inside the solenoid both ions have to pass a thin carbon foil, where the last electron of the H_2^+ ions is stripped off and, therefore, two protons are produced. These protons share the kinetic energy of the H_2^+ ion and can be separated by the Wien filter of the LSP from the protons, which originate from the initial atoms. In this way, the nuclear polarization of the atoms and the molecules can be measured under various conditions.

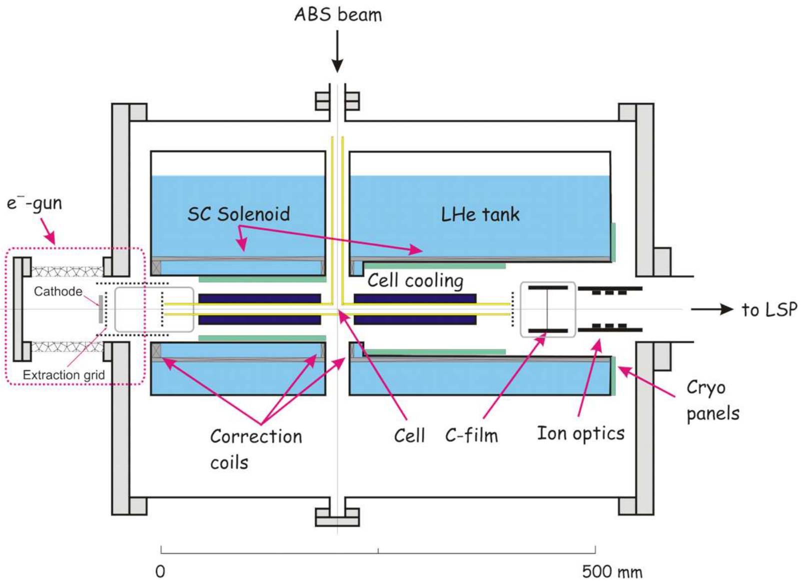

Fig. 4. Setup of the experiment to measure the polarization of hydrogen (deuterium) molecules after recombination of polarized atoms.

After solving a long list of minor problems, in the summer of 2009 first experiments were performed on a gold surface. They showed the surprising result shown in Fig. 5. The polarization for a fixed magnetic field was stable even at low temperatures as low as 47 K. Until now, no material has been found which could preserve the polarization at temperatures below 80 K.[19]

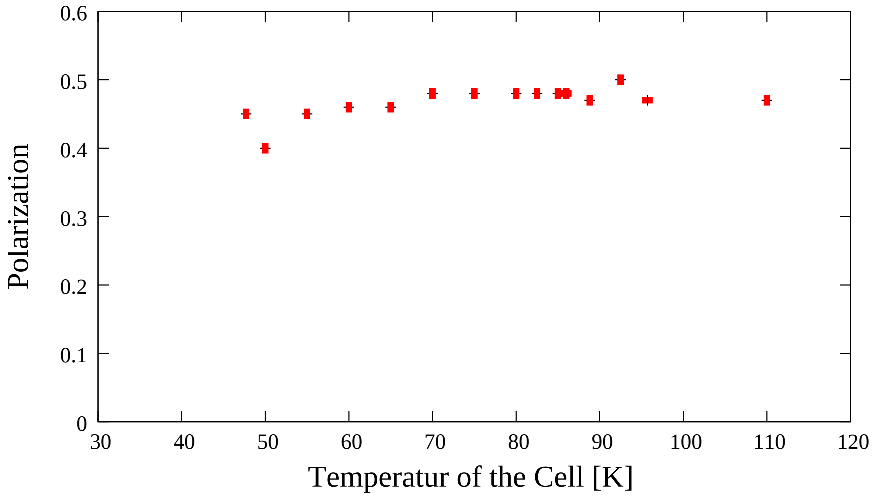

Fig. 5. One of the first results with polarized hydrogen atoms in a storage cell with a gold surface. The polarization for atoms in HFS 1 is stable and independent of the temperature. (Magnetic field: 0.28 T, ion beam energy: 4 keV)

4. Rare Neutron Decay

In the neutron decay $n \rightarrow p + e + \bar{\nu}_e$ the proton and electron can be found in different bound S states of the hydrogen atom.[20] The kinetic energy of 326.5 eV for this 2-body decay fits to the energy range of the Lamb-shift polarimeter. Therefore, the polarization of the metastable hydrogen atoms can be measured, i.e., the proton and electron spin after the decay. If the helicity of the antineutrino is completely positive (right-handed), then the probabilities to find the different combinations of electron and proton spin, i.e. the different Zeeman states of the hydrogen atom, can be calculated and tested with this experiment. Therefore, left-handed admixtures to the helicity or scalar and tensor contributions to the weak force can be measured with high precision.[21,22] The challenge of the experiment is the low count rate of metastable hydrogen atoms behind the spinfilter. For the throughgoing FRM II beam tube less than 1 count per second is expected. For the detection of the outgoing atoms 4 different methods are suggested:

- Ionization of the metastable atoms only by 2 different lasers and collection of the outcoming protons (Efficiency: $\sim 50\%$).
- Detection of the Lyman-α photons after quenching the metastable atoms with a photomultiplier and a setup of optimized mirrors (Efficiency: $\sim 5\%$).
- Detection of the Lyman-α photons by photoeffect on a CsI or a tungsten surface and collection of the electrons with a channeltron (Efficiency: $> 50\%$).
- Selective charge exchange of metastable hydrogen atoms with argon and separation of the H^- ions produced by a velocity filter (Efficiency: $\sim 10\%$).

Which method will give the best signal-to-noise ratio and a reasonable efficiency will be tested at the Technical University of Munich, Physik Department E18.

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